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FULL-SCALE TESTS OF SEVERAL PROPELLERS EQUIPPED WITH  
SPINNERS, CUTTS, AIRFOIL AND ROUND SHANKS, AND  
NACA 16-SERIES SECTIONS

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SUMMARY

Wind-tunnel tests of several propeller, cuff, and spinner combinations were conducted in the 20-foot propeller-research tunnel. Three propellers, which ranged in diameter from 8.4 to 11.25 feet, were tested at the front end of a streamline body incorporating spinners of two diameters. The tests covered a blade angle range from  $20^{\circ}$  to  $65^{\circ}$ . The effect of spinner diameter and propeller cuffs on the characteristics of one propeller was determined. Tests were also conducted using a propeller which incorporated aerodynamically good shank sections; and using one which incorporated the NACA 16-series sections for the outer 20 percent of the blades. Compressibility effects were not measured, owing to the low testing speeds.

The results indicated that a conventional propeller was slightly more efficient when tested in conjunction with a 28-inch-diameter spinner than with a 23-inch spinner, and that cuffs increased the efficiency as well as the power absorption characteristics. A propeller having good aerodynamic shanks was found to be definitely superior from the efficiency standpoint to a conventional round-shank propeller, with or without cuffs; this propeller would probably be considered structurally impracticable, however. The propeller incorporating the NACA 16-series sections at the tips was found to have a slightly higher efficiency than a conventional propeller; the take-off characteristics appeared to be equally good.

The effects noted above probably would be accentuated at helical speeds at which compressibility effects would enter.

## INTRODUCTION

There are a number of obvious methods for improving the performance of conventional propellers. Studies of propeller losses have indicated that the profile drag of the blade sections is responsible for several-percent loss in efficiency at low helical speeds and considerably greater losses at speeds beyond the critical. This is particularly true for the nearly round shank sections. The methods available at the present for remedying the shank problem consist of: (a) employing a large spinner to house the poor sections, (b) use of cuffs to streamline the blade shanks, and (c) employing good airfoil sections for the shanks, which may not be practicable owing to strength considerations. Improvements in the outer portions of blades require the use of low drag sections having high critical speeds.

Although there seems to be little doubt that the modifications listed will result in some improvement if properly carried out, there is little quantitative information on these subjects and consequently there is certain hesitancy in adopting them.

The purpose of this paper is to present the results of several miscellaneous propeller tests which embodied these methods for improving the efficiency and increasing the critical speed. These tests were made incidental to a dual-rotating propeller program (see reference 1) and employed the same apparatus with the exception of cuffs and two additional propellers. In this paper results of the following tests are described:

- (a) Two spinner sizes
- (b) Cuffs
- (c) A racing propeller embodying airfoil shanks
- (d) A propeller employing NACA 16-series sections at the propeller tips

Unfortunately, compressibility effects could not be measured, owing to the low testing speed; low-speed characteristics of devices calculated to increase the critical speeds were measured, however, and are of considerable interest in assaying the general utility of such devices.

High-speed-tunnel test results of airfoil sections and basic shapes are available, however, which can be used for determining critical speeds of propeller tips, shanks, and cuffs. (See references 2 and 3.)

## APPARATUS AND METHODS

The tests were made in the NACA 20-foot propeller-research tunnel, using the same general testing apparatus that was used for testing dual-rotating propellers. (See reference 1.)

Test set-up.- A sketch and a photograph of the set-up are given in figures 1 and 2, respectively. No wing was used for these tests. The propellers were driven by two 25-horsepower electric motors arranged in tandem and geared together. The motors were mounted on bearings concentric with the shaft axis and were restrained from rotating by helical springs connecting the motor frame with the supporting frame. Selsyn units were used to indicate the movements of the motor frames to observers in the balance house, in order that torque measurements could be made. The springs were calibrated for torque at the beginning and the end of the tests, and several friction calibrations were made during the tests.

Inasmuch as the set-up was built for testing dual-rotating propellers, it was possible to locate single propellers either on the front shaft or on the rear shaft, thus providing two spinner-size conditions. It may be noted from figure 1 that the front spinner was approximately 23 inches in diameter, while the rear one was 28 inches in diameter.

Propellers.- Three propellers of different designs were tested. Propeller 3155-6 is the right-hand design used in the dual-rotating program. Propeller 1555-2 is of a design built for a Navy racing seaplane more than 12 years ago. It was tested because it appeared to be of good aerodynamic shape with respect to the shank sections, pitch distribution, and plan form. It would not be considered structurally safe, as judged by our present standards. Both the 3155-6 and 1555-2 propellers have Clark-Y sections. Propeller 6193A-3 is a new Hamilton Standard design which incorporates the NACA 16-series sections over the outer 20 percent of the blades. (See reference 2 for



section data.) Although the chief purposes of these sections is to delay the compressibility burble, it was thought that tests at low speeds would be of interest, particularly because some concern has been expressed regarding the take-off qualities of the new sections.

A photograph of the three propeller blades is given in figure 3, while the blade-form curves are given in figure 4. The table (p. 5) gives other pertinent information.

Cuffs.— Cuffs were designed for propeller 3155-6 for use with the 23-inch spinner. Three basic designs were made; each design was for a specific high-speed blade setting ( $\beta$  at  $0.75R = 30^\circ, 45^\circ, 60^\circ$ ). A sketch of the cuffs is given in figure 5. In designing the cuffs, it appeared that a reasonably well-shaped cuff could be obtained by the use of two sections 15 inches apart, the outer section being the propeller section at the 27-inch radius, while the inner was a symmetrical section located at the 12-inch radius. The base symmetrical section was of an arbitrary design intended to have a low drag coefficient and a high critical speed. It was approximately 27 percent thick. In figure 6 is given the basic section outline together with its theoretical pressure distribution for  $C_L$  values of 0.0 and 0.2. Although the basic section is not the optimum as regards critical speed for a given fineness ratio, it is a good section in that it combines a fairly high critical speed with low drag at low speeds. The computed theoretical critical Mach number is approximately 0.69 and 0.66 for  $C_L$  values of 0.0 and 0.2, respectively. These critical Mach numbers correspond to approximately 525 and 505 miles per hour, respectively, at sea level.

In figure 7 are given the data used in obtaining the base section angle setting for each of the three designs. The blade section angle curves were first determined from the propeller drawings for the three design blade settings, using the chord lines as reference. The curves for section angles, measured from the section zero lift line, were then determined, using Clark Y airfoil data given in figure 8. The zero-line lift curves become indeterminate as they approach the zero radius stations, because these sections become cylinders; they have been arbitrarily faired into a  $90^\circ$  angle at the zero radius. The helical air angles were then computed for all stations, considering the forward and rotational component velocities of

Drawing number	Number of blades	Diameter	<sup>a</sup> Activity factor (per blade)	Section	Spinner diameter used (in.)
Ham.-Stand. 3155-6	3	10	89.7 91.3 (with cuffs)	Clark-Y	23 and 28 23
Bureau Aero. 1555-2	2	8.4	78.4	Clark-Y	23
Ham.-Stand. 6193A-3	3	11.25	97.4	<sup>b</sup> Clark-Y NACA 16 series	28

$$^a\text{Activity factor} = \frac{100000}{16} \int_{0.2}^{1.0} b/D (r/R)^3 d(r/R)$$

<sup>b</sup>Clark-Y section      r/R from 0.2 to 0.71  
 NACA 16-series section      r/R      "      .8      "      1.0  
 Transition      "      r/R      "      .71      "      .8

each section. The difference between the helical air angle and the zero-lift section angle is equal to the sum of the angle of attack measured from the zero-lift line and the inflow angle. In view of the uncertainty of the inflow angle, particularly for the propeller root sections, there is little point in trying to isolate it. The inflow angle is ordinarily roughly about half the angle of attack. The cuff base section at the 12-inch station was set approximately at angles of attack plus inflow angles of  $5^\circ$ ,  $3^\circ$ , and  $3^\circ$ , for the  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$  designs, respectively. The lift-coefficient for the cuff base section of the  $30^\circ$  design would appear to be about the same as that for the rest of the blade, but about half that for the outer parts of the blade for the  $45^\circ$  and  $60^\circ$  settings. This effective wash-out of the cuff for the higher blade-angle designs was introduced to minimize the loading on the cuff and consequently minimize the rotational losses, and also to obtain a high critical speed. No account was taken of the induced velocities over the spinner. These would have the effect of reducing the angle of attack slightly.

Measurements.— Tests were conducted according to standard test procedure used for this tunnel. (See reference 1.) The tunnel speed ranged from 0 to about 110 miles per hour; the maximum propeller speed was about 550 revolutions per minute, which corresponds to 287 feet per second rotational tip speed for a 10-foot diameter propeller. It is obvious from this that no compressibility effects could be measured.

## RESULTS AND DISCUSSION

The measured values have been reduced to the usual coefficients of thrust, power, propulsive efficiency, and speed-power.

$$C_T = \frac{\text{effective thrust}}{\rho n^2 D^4}$$

$$C_P = \frac{\text{engine power}}{\rho n^3 D^5}$$

and

$$\eta = \frac{C_T}{C_P} \frac{V}{nD}$$

$$C_s = \sqrt[5]{\frac{\rho V^5}{P n^2}}$$

where the effective thrust is the measured thrust of the propeller-body combination plus the drag of the body measured separately,

$\rho$  density

$D$  propeller diameter, feet

$V$  air speed, fps

$n$  propeller rotational speed, rps

and  $P$  power

In figure 9 are sample characteristic curves drawn through the test points which give an indication of the accuracy of the data.

The test results are presented in the following figures:

Figure	Test	Propeller drawing	Number of blades	Diameter of spinner (in.)
10 to 12	Spinner size	3155-6	3	23 & 28
13 to 16	Cuff	3155-6	3	23
17 to 19	Racing propeller (airfoil shanks)	1555-2	2	23
20	Spinner, cuff, and shank shape comparisons	3155-6 & 1555-2	2 & 3	23 & 28
21 to 25	NACA 16-series sections	6193A-3	3	28



Spinners.— Of the three methods for treating the shank problem, the use of large spinners is perhaps the most direct and the simplest, provided good lines can be obtained with the rest of the body. Relatively large spinners can be used for certain applications with liquid-cooled engines and special types of cowling designed for air-cooled radial engines. Large spinners, however, defeat the purpose of extension shafts where the object is to reduce the body size and the wetted area. Unless cuffs are used, a balance should be struck between the drag produced by the poor blade shanks and the drag produced by the large spinner and the shaft housing.

Although the data obtained from these tests are limited to two spinner sizes, the results are considered to be of sufficient interest to warrant publication. It may be noted by referring to figures 10 to 12 and figure 20 that the propeller when tested in the rear position with the 28-inch spinner absorbed slightly more power and produced more thrust at the higher blade settings than when tested in the front position with a 23-inch spinner. The efficiency was between 1 and 2 percent higher for the large spinner. There appears to be no ready explanation for the differences in power noted for the spinner conditions. The large spinner-propeller combination should produce slightly more thrust, however, and result in a higher efficiency than a smaller spinner-propeller combination, owing to the fact that about  $2\frac{1}{2}$  inches of additional cylindrical shank are submerged within this large spinner.

Cuffs.— The use of propeller cuffs in conjunction with a relatively small spinner offers a means for improving the propeller characteristics without necessitating the use of a large body. Propeller cuffs, however, have never been shown to be an ideal solution of the problem because they are difficult to build and maintain, and no great benefits have been demonstrated from their use, other than for ground cooling of radial engines. There seems to be little doubt, however, that cuffs will reduce the drag of exposed cylindrical propeller shanks, particularly at speeds beyond the critical for these sections. In reference 3 the critical speed for circular cylinders is shown to occur at approximately 310 miles per hour at sea level ( $M_c = 0.4$ ). At speeds beyond the critical the rate at which the drag increases is shown to be much less

than for airfoils operating at low angles of attack, which would indicate that the greatest gain due to the use of cuffs would result from eliminating separation at the shanks and only a small additional gain would result from eliminating compressibility effects. Recent unpublished data indicate, however, that the drag of 4-inch-diameter cylinders is more affected by compressibility than the drag of the small ones used for the tests reported in reference 3.

In figures 13 to 16 are presented the characteristic curves of a propeller tested with and without cuffs. It may be noted that the cuffs added appreciably to the thrust and power of the propeller, particularly for the stall operating range. The cuffs apparently stalled at approximately the same angle as the rest of the blade, since the peak of the thrust and power curves occurs at about the same  $V/nD$  with and without the cuffs. The efficiency of the propellers increased 1 to 2 percent with the use of cuffs. (See also fig. 20.) A greater difference would be expected for high-speed airplanes.

A rough analysis intended to determine an average lift coefficient of the cuff sections when operating at the peak propeller efficiency indicates that the cuffs designed for the  $30^\circ$  and  $45^\circ$  blade-angle settings were operating at a lift coefficient of approximately 0.2. The  $C_L$  for the  $60^\circ$  blade angle was approximately 0.14. The average lift coefficient for the remainder of the blades was probably greater than 0.4, which indicates that the large increment of thrust attributed to the cuffs was due to the large area added.

The effect of increasing or decreasing the angle of the base section of the cuff can be noted from the results given in figures 13 to 15. As previously noted, the three cuffs were designed for three blade-angle settings,  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$ , measured at the three-fourths radius; each of these designs was tested at blade angles of  $5^\circ$  below the design condition, and  $5^\circ$  above the design condition. Since cuffs require more twist for low blade-angle settings than for high ones, it is obvious that the cuffs, when tested at the reduced angles,  $25^\circ$ ,  $40^\circ$ , and  $55^\circ$ , were effectively washed out at the base section,

approximately  $2\frac{1}{2}^\circ$ . Likewise, the base sections were washed in approximately  $2\frac{1}{2}^\circ$  for the  $35^\circ$ ,  $50^\circ$ , and  $65^\circ$

tests. The effect of either the wash-in or the wash-out is quite apparent in the results. For example, the thrust added by the cuff for the  $40^\circ$  blade angle is appreciably less than for the design blade angle of  $45^\circ$ , and the thrust added by the cuff for the  $50^\circ$  blade angle is about double the thrust added for the design blade angle of  $45^\circ$ . It is quite obvious from this that the angle setting for the cuff is very important, especially for cuffs of this design.

If cuffs were designed for the highest possible critical speed, a slightly lower angle of attack might be desirable than was present for these tests. An estimate of the angles for any desired condition may be obtained by correlating the design curves given in figure 7 with the data obtained from the tests.

It is unfortunate that these cuffs were not tested at speeds above 310 miles per hour because it is expected that their effect on the efficiency would be greater at those speeds than was measured for these tests. There is no way at present of estimating the gain in efficiency above the critical speeds of any section, because wind-tunnel data are generally limited to speeds only slightly above the critical because the drag of cylinders increases so rapidly at those speeds that it is not possible to obtain higher tunnel speeds. This was particularly true in the case of recent high-speed tests with 4-inch cylinders.

Propeller 1555-2.— This propeller was designed for a racing airplane more than 12 years ago. It was tested, along with two modern propellers, in this series of tests because it incorporated a good aerodynamic shape. This racing propeller was built with airfoil shanks extending to within the 23-inch-diameter spinner shell. The pitch-diameter ratio was about constant for a blade setting of  $30^\circ$ . (See fig. 4(b).) At blade angles above  $40^\circ$  the pitch-diameter ratio for the root section is quite excessive and, since these sections are fairly wide and of good airfoil shape, the efficiency would be expected to suffer at high blade angles because of this.

The good aerodynamic shape of this propeller resulted in a high efficiency for the blade settings for which it was designed, namely, between  $20^\circ$  and  $40^\circ$ . (See figs. 17 to 19.) This propeller is several percent higher in efficiency than propeller 3155-6 in the  $V/nD$  range up to 2.4,

even when cuffs were added to 3155-6. At higher values of  $V/\alpha D$  propeller 1555-2 did not show up so well, probably because the shank sections were being loaded up too high. The high efficiency of propeller 1555-2 (over 90 percent) is attributed chiefly to its relatively thin, well-shaped shanks, and partly to the plan form, which is also different from that of propeller 3155-6. Although the 1555-2 plan form may be somewhat superior to that of 3155-6 from the efficiency standpoint, it should be noted that the latter is superior from the standpoint of absorbing high power and consequently it may be preferable for high-output engines. The activity factor, which is an index of the power-absorbing qualities, is 78.4 for propeller 1555-2 as compared with 89.7 for propeller 3155-6.

Propeller 6193A-3. - Propeller 6193A-3 was tested because it embodied the NACA 16-series sections for the outer 20 percent of the blades. The 16-series sections were developed primarily to delay the compressibility burble (reference 2) and consequently are particularly adaptable to propellers which operate as close to the speed of sound as is practicable. Since compressibility effects could not be measured in these tests, the chief interest was the behavior of the sections at low speeds and at operating conditions corresponding to the take-off and climb, for which wind-tunnel tests of airfoils are inconclusive. Results are given in figures 21 to 25, which include a  $C_s$  design chart and a comparison with propeller 3155-6. It may be noted that even at the low speeds of these tests, propeller 6193A-3 was from 1 to 3 percent more efficient than propeller 3155-6. It should be remembered, however, that these propellers are not strictly comparable because of differences in diameter and blade shape. Of particular interest is the fact that propeller 6193A-3 exhibits no unusual stalling characteristics. Consequently, if these low-speed tests are indicative of the stalling properties at higher speeds, it appears that the 16-series section is at least the equal of the Clark-Y from this standpoint.

#### CONCLUDING REMARKS

These tests, which were confined to low tip speeds, indicate that:

Of the three methods investigated for improving the

propeller characteristics by virtue of improving the shank shape, increasing the spinner size from 23 to 28 inches in diameter resulted in an improvement in efficiency of from 1 to 2 percent; installation of large-chord propeller cuffs improved the efficiency of the small propeller-spinner combination also 1 or 2 percent; while a propeller designed with good aerodynamic shanks was found to be several percent more efficient than the conventional round-shank propeller. A propeller incorporating the NACA 16-series sections over the outer 20 percent of the blade was found to have a slightly higher efficiency than a conventional propeller incorporating Clark-Y sections for the entire blade, even at low tip speeds. The take-off properties of the two propellers appeared to be about equal.

The differences noted between the various propeller-spinner-cuff combinations would be expected to be greater than indicated in this report, if the effects of compressibility had been present; hence these results are all conservative.

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Langley Field, Va.

#### REFERENCES

1. Biermann, David, and Hartman, Edwin P.: Full-Scale Tests of 4- and 6-Blade Single- and Dual-Rotating Propellers. NACA conf. rep., 1940.
2. Stack, John: Tests of Airfoils Designed to Delay the Compressibility Burble. NACA conf. rep., 1939.
3. Lindsey, W. F.: Drag of Cylinders of Simple Shapes. Rep. No. 619, NACA, 1938.

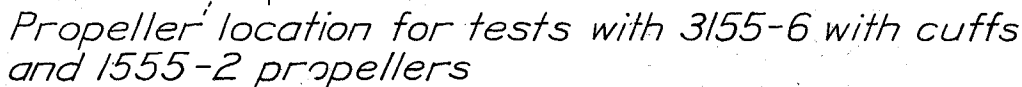


Figure 1.- Plan view showing dimensional details of nacelle.

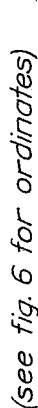
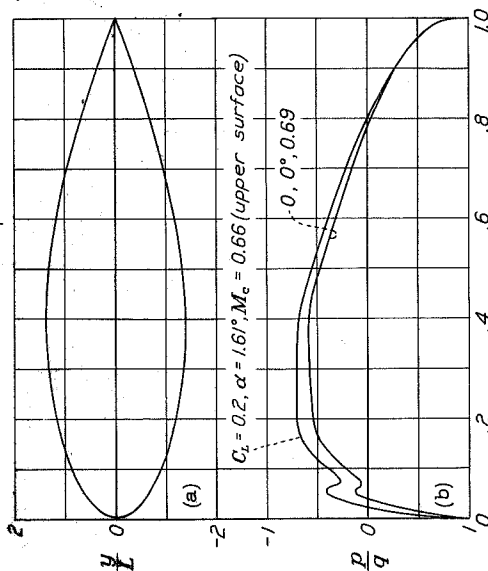
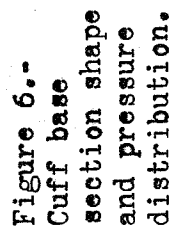


Figure 5.-  
Sketch of propeller cuff  
showing dimensional details.



(a) Cuff base section shape. (b) Theoretical pressure distribution.



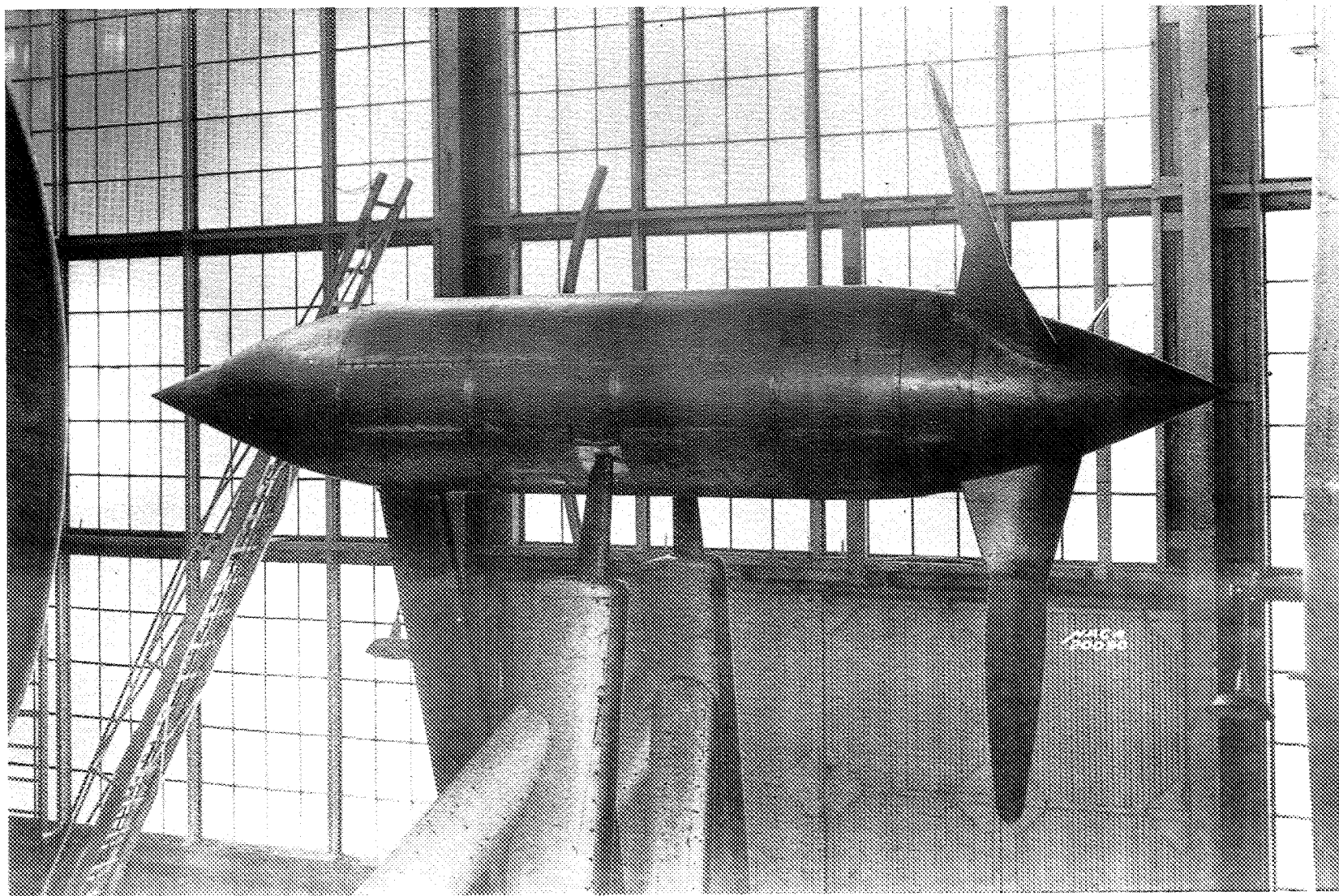


Figure 2.- Set-up showing cuff installation.

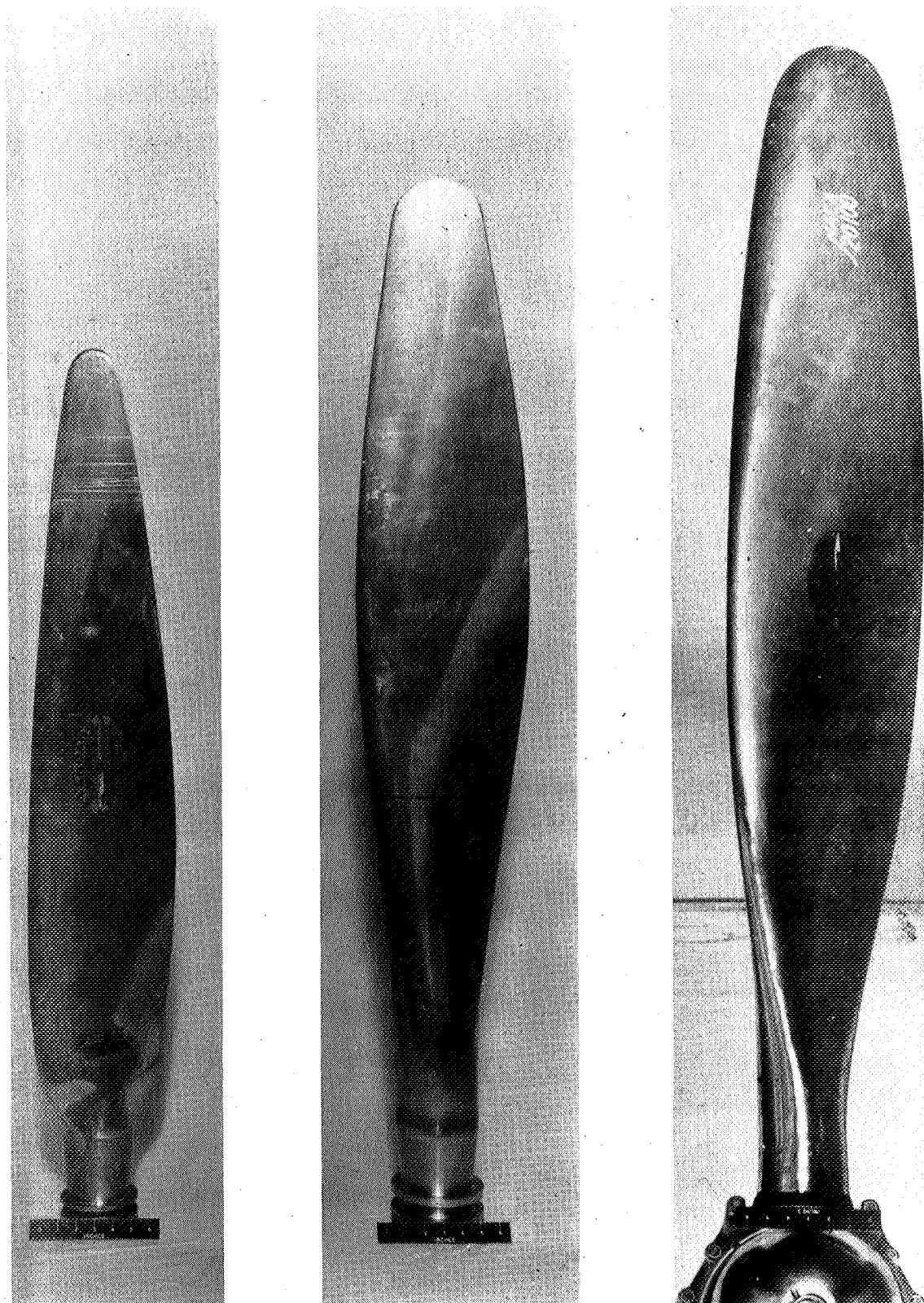


Figure 3.- Propellers 1555-2, 3155-6, and 6193A-3.

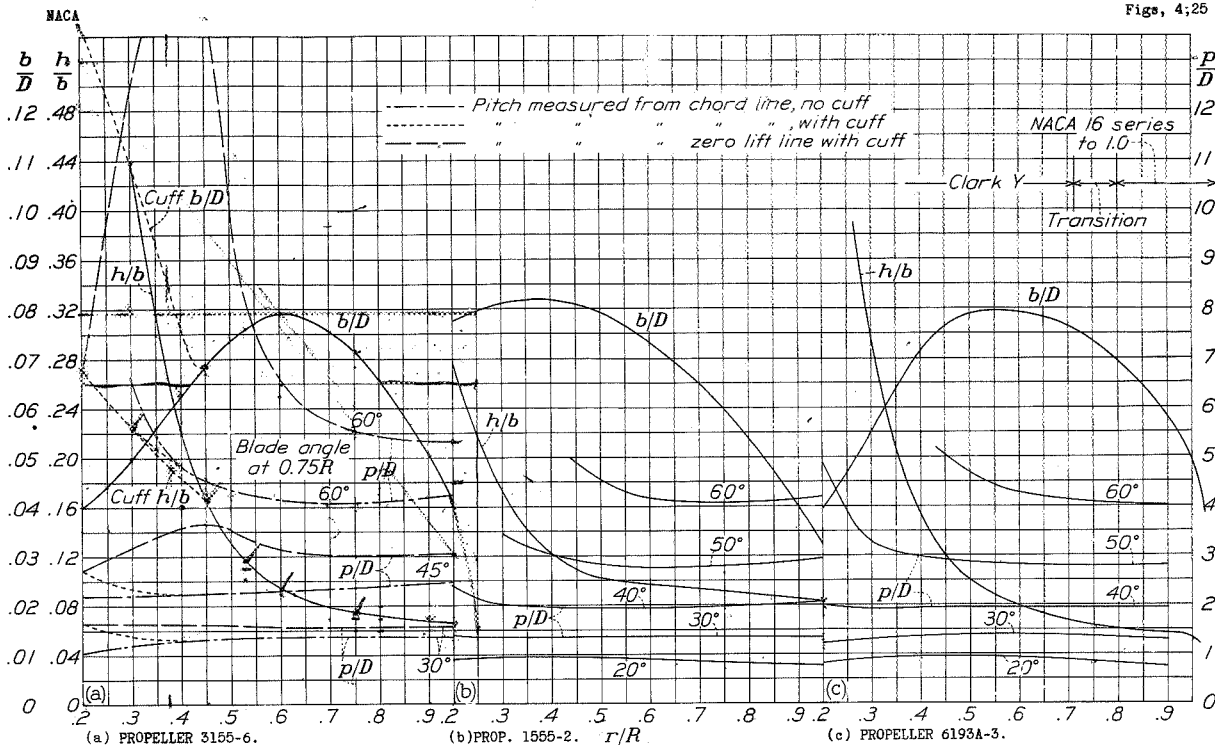


FIGURE 4.- BLADE-FORM CURVES FOR PROPELLERS----- WITH AND WITHOUT CUFFS. D, DIAMETER; R, RADIUS TO THE TIP; r, STATION RADIUS; b, SECTION CHORD; h, SECTION THICKNESS; p, GEOMETRIC PITCH.

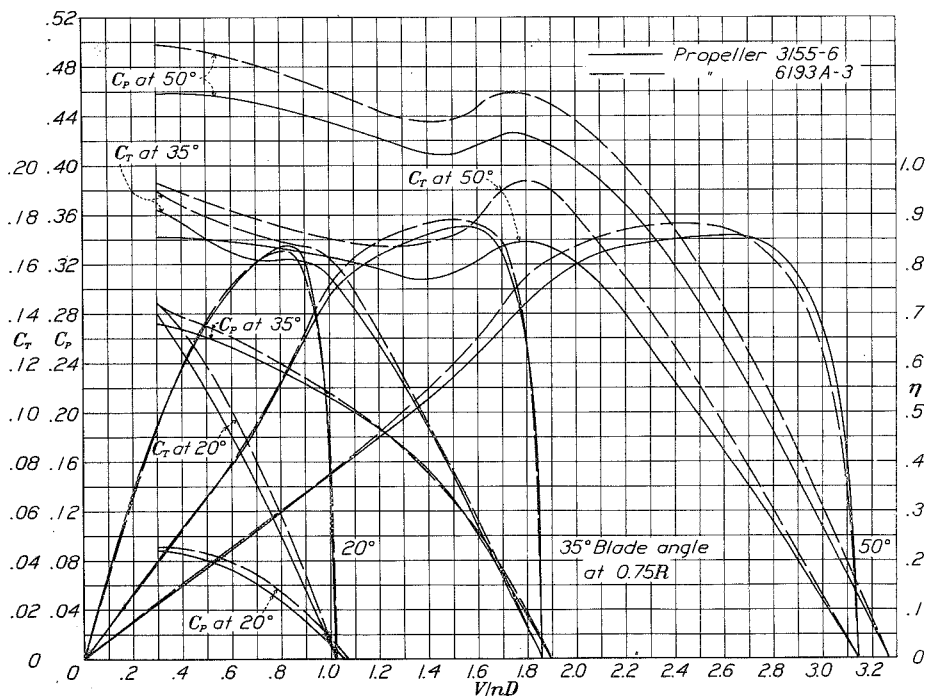


FIGURE 25.- INTERPOLATED CHARACTERISTICS CURVES OF PROPELLER 6193A-3 SUPERPOSED ON CURVES OF PROPELLER 3155-6.

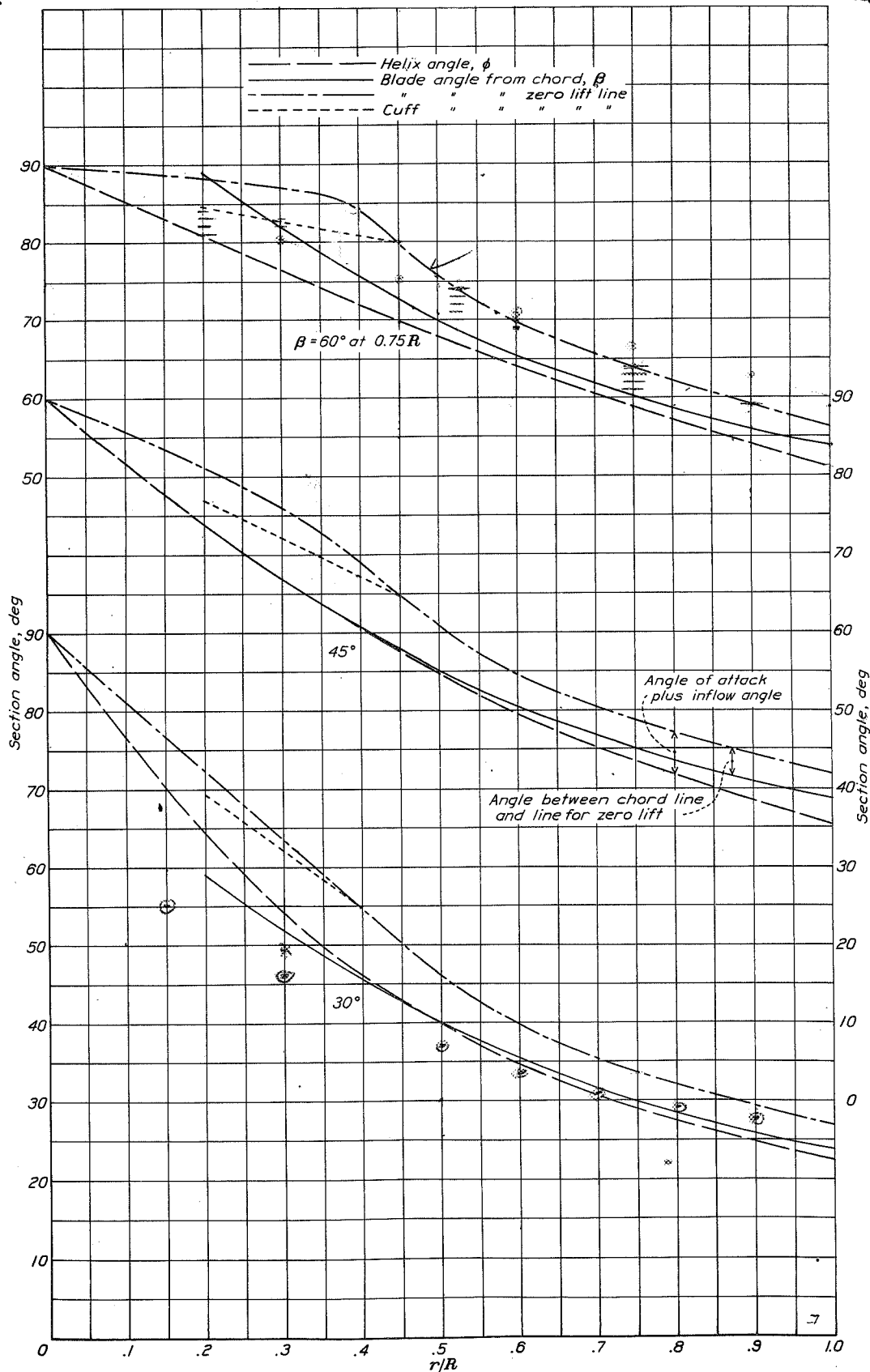


FIGURE 7.- GUFF DESIGN CURVES FOR PROPELLER 3155-6.

FIGURE 8.-

CLARK Y

AIRFOIL

COEFFICIENTS

AT

INFINITE  $\rightarrow$  WRONG  
ASPECT RATIO

ASPECT

RATIO = 6

RV:  $3 \times 10^6$

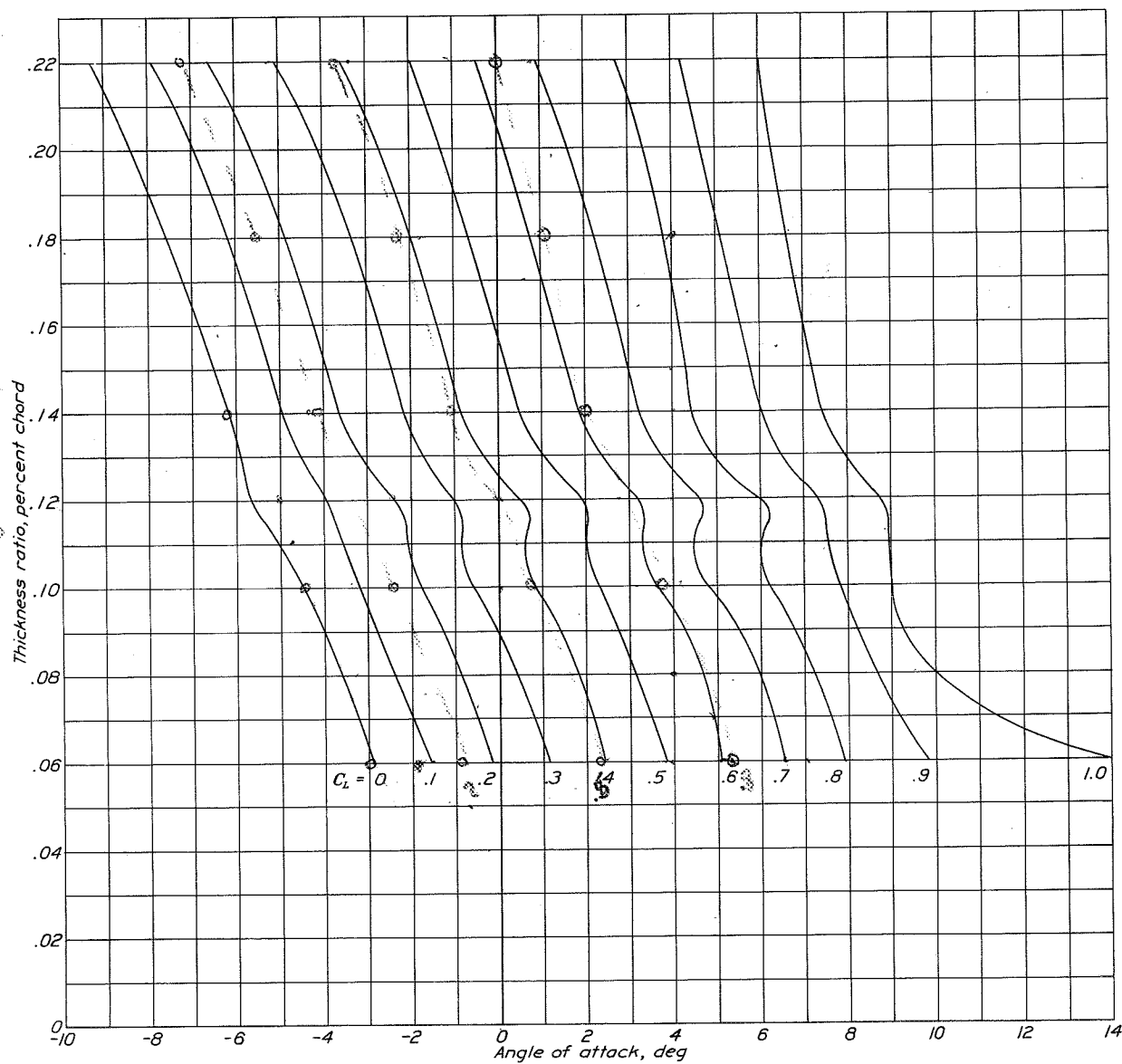


FIGURE 9.-  
TYPICAL  
TEST  
RESULTS.  
(PROPELLER  
3155-6  
WITH  
CUFFS  
SET AT  $50^\circ$   
AT 0.75R.)

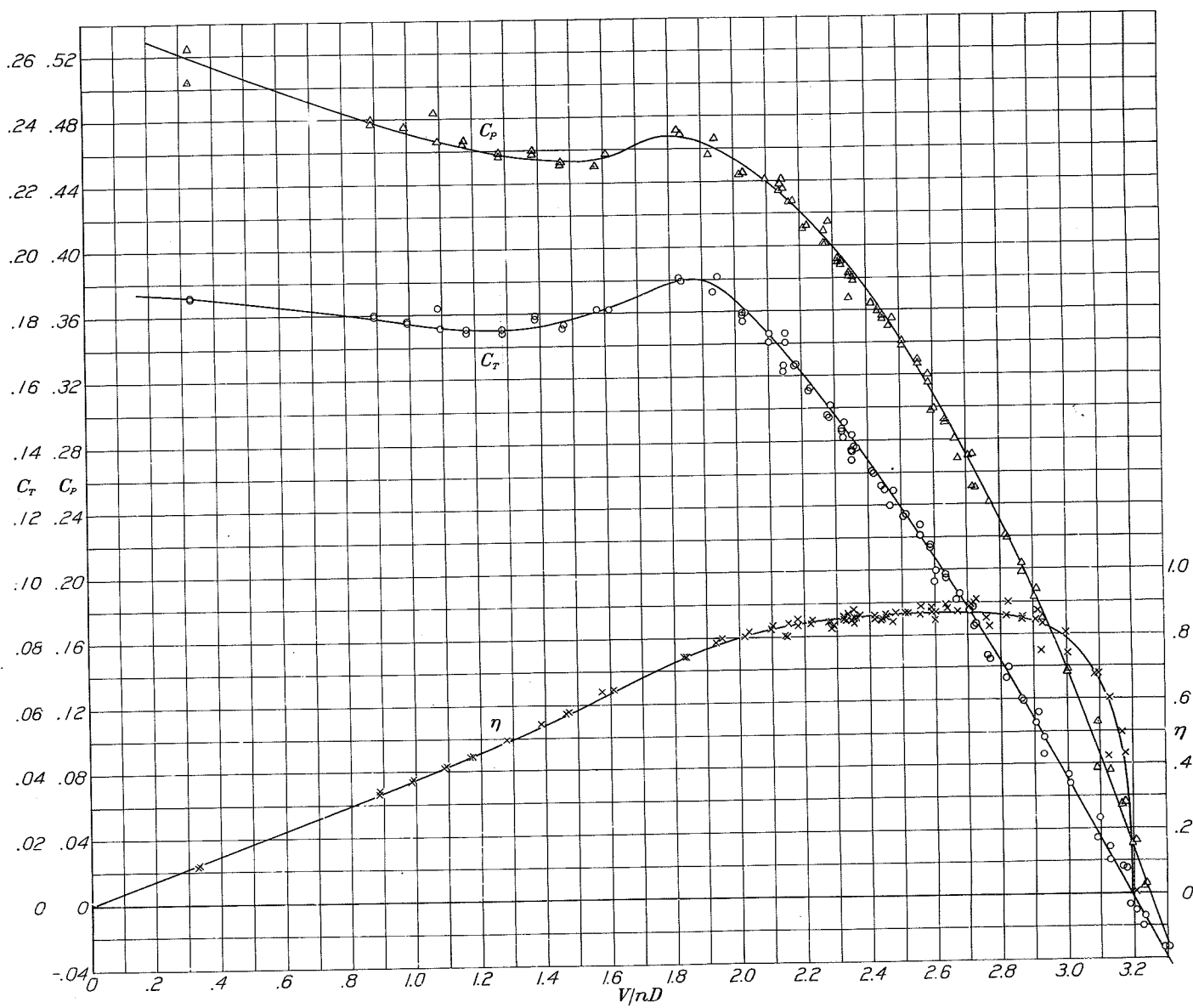


Fig. 9



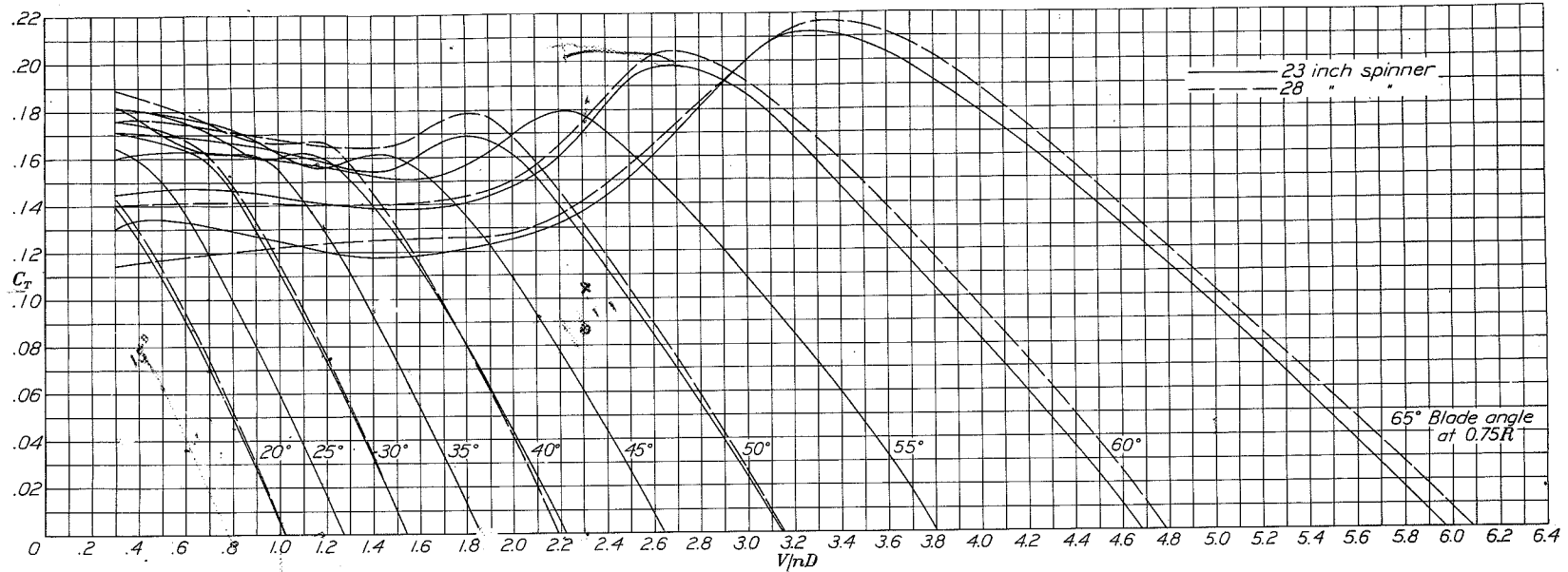


FIGURE 10.- THRUST-COEFFICIENT CURVES FOR THREE-BLADE PROPELLER 3155-6 TESTED WITH TWO SPINNER SIZES.

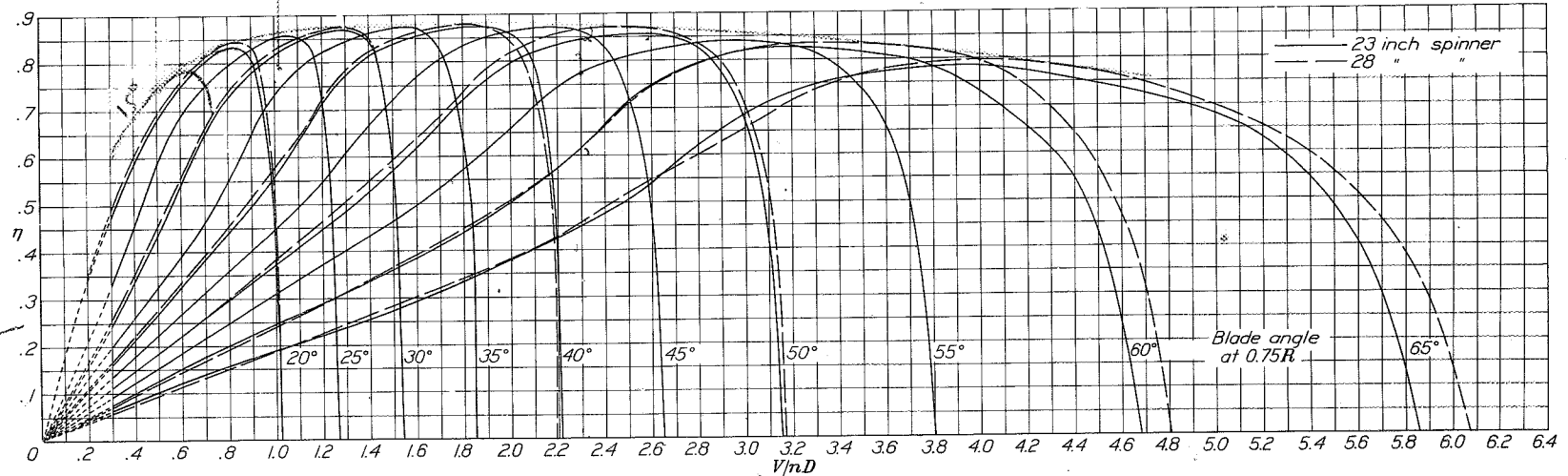


FIGURE 12.- EFFICIENCY CURVES FOR THREE-BLADE PROPELLER 3155-6 TESTED WITH TWO SPINNER SIZES.

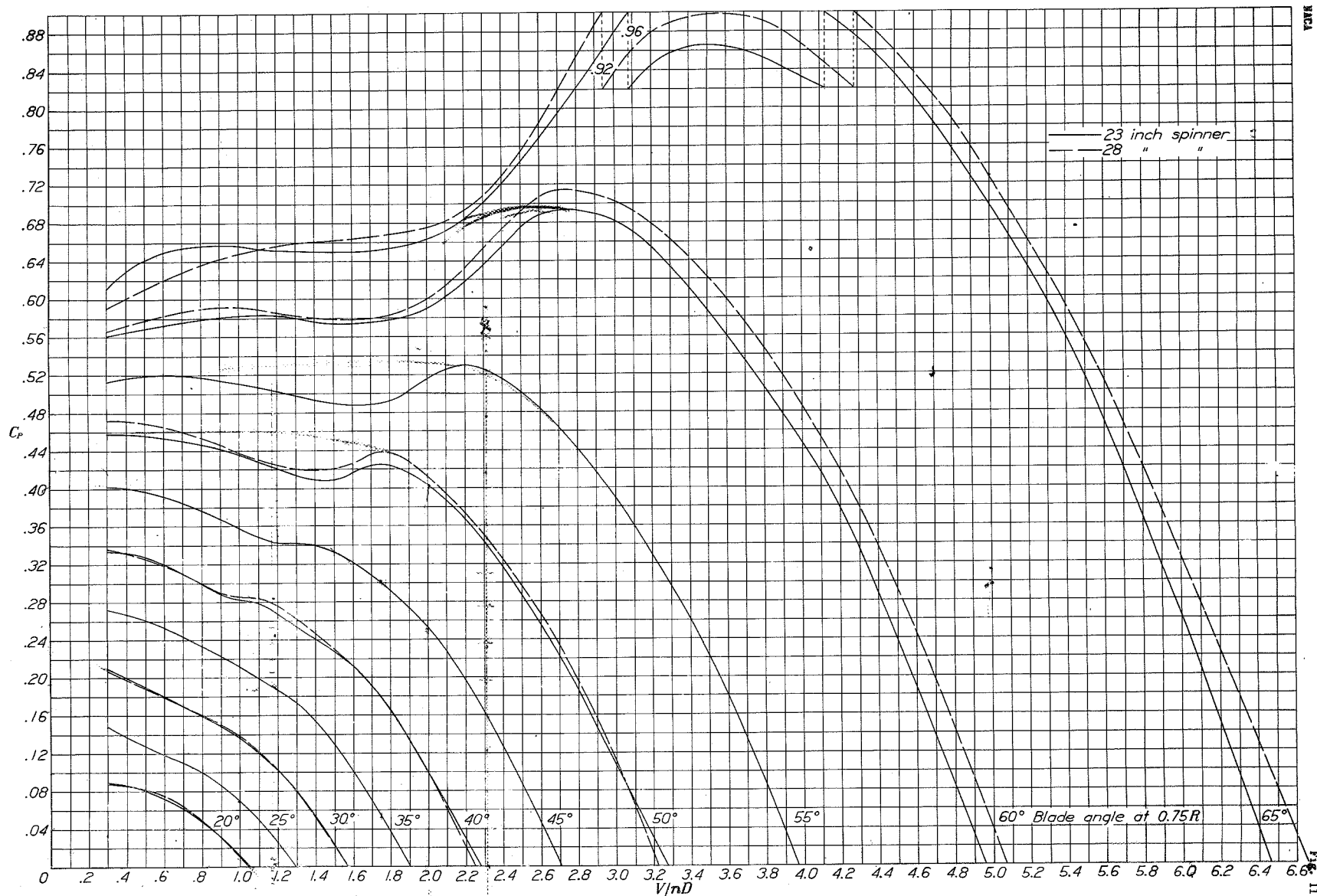


FIGURE 11.- POWER-COEFFICIENT CURVES FOR THREE-BLADE PROPELLER 3156-6 TESTED WITH TWO SPINNER SIZES.

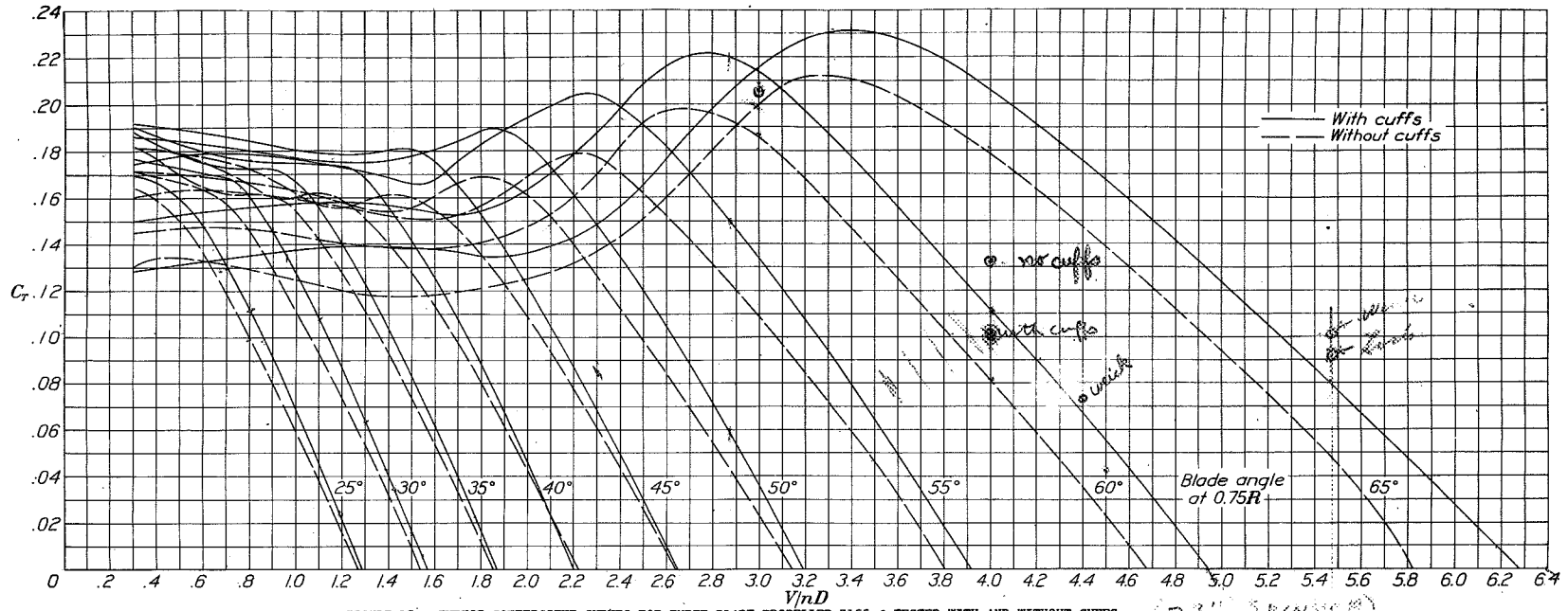


FIGURE 13.- THRUST-COEFFICIENT CURVES FOR THREE-BLADE PROPELLER 3155-6 TESTED WITH AND WITHOUT CUFFS.

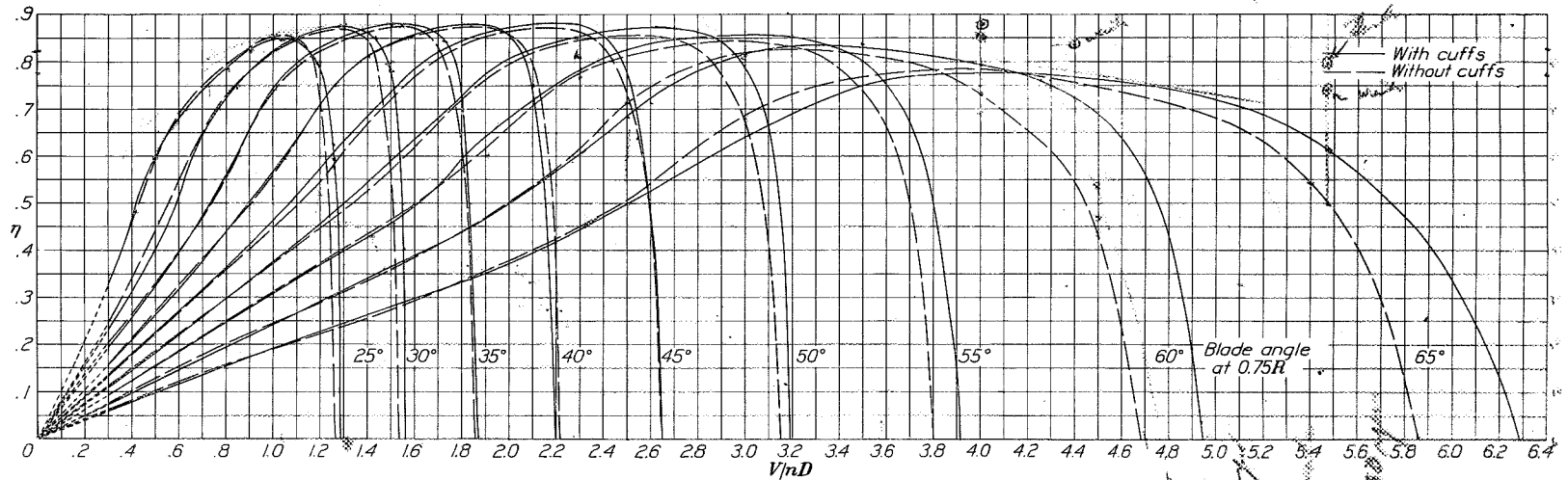


FIGURE 15.- EFFICIENCY CURVES FOR THREE-BLADE PROPELLER 3155-6 TESTED WITH AND WITHOUT CUFFS.

For cuff atting see page 9

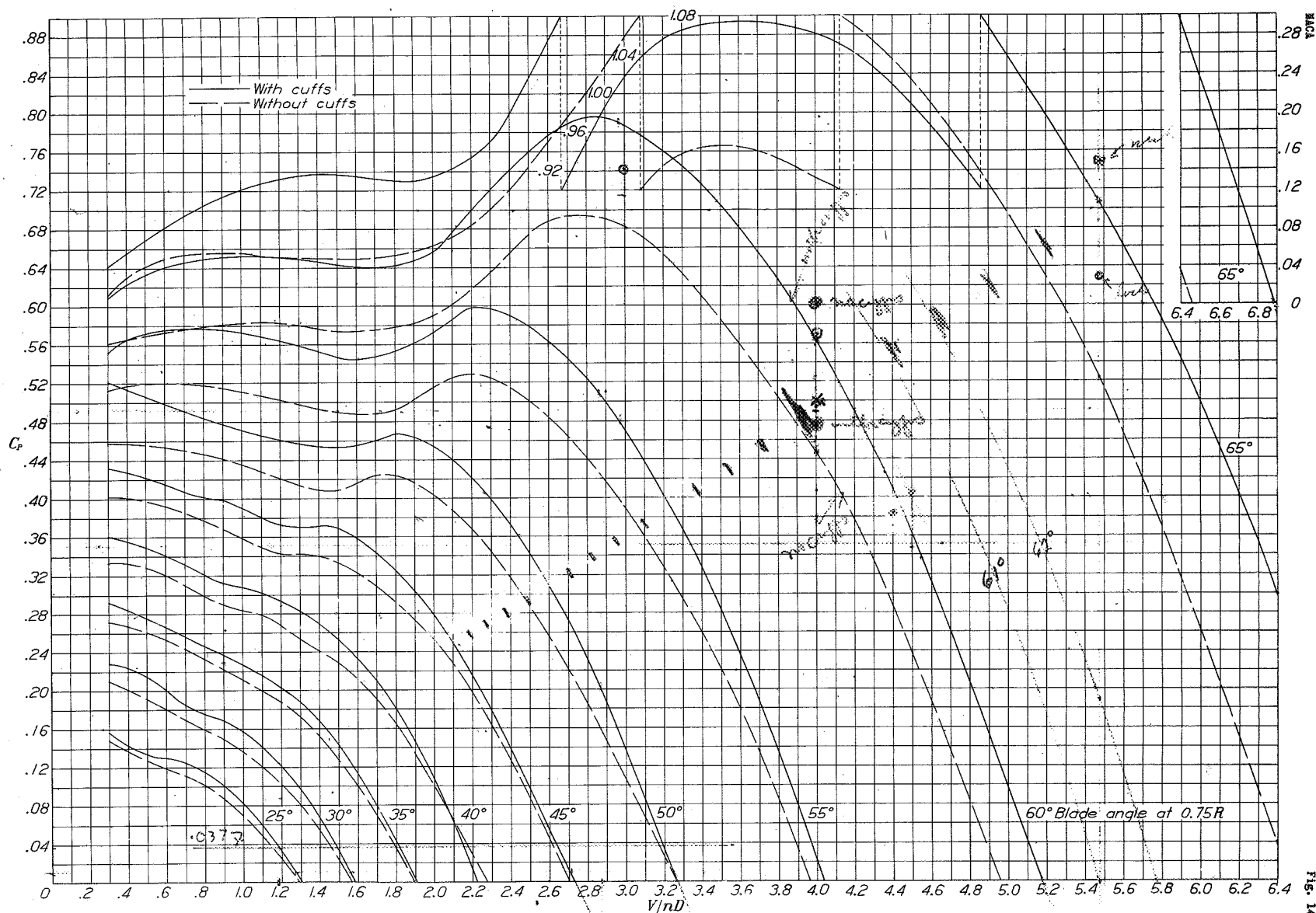


FIGURE 14.- POWER-COEFFICIENT CURVES FOR THREE-BLADE PROPELLER 3155-6 TESTED WITH AND WITHOUT CUFFS.

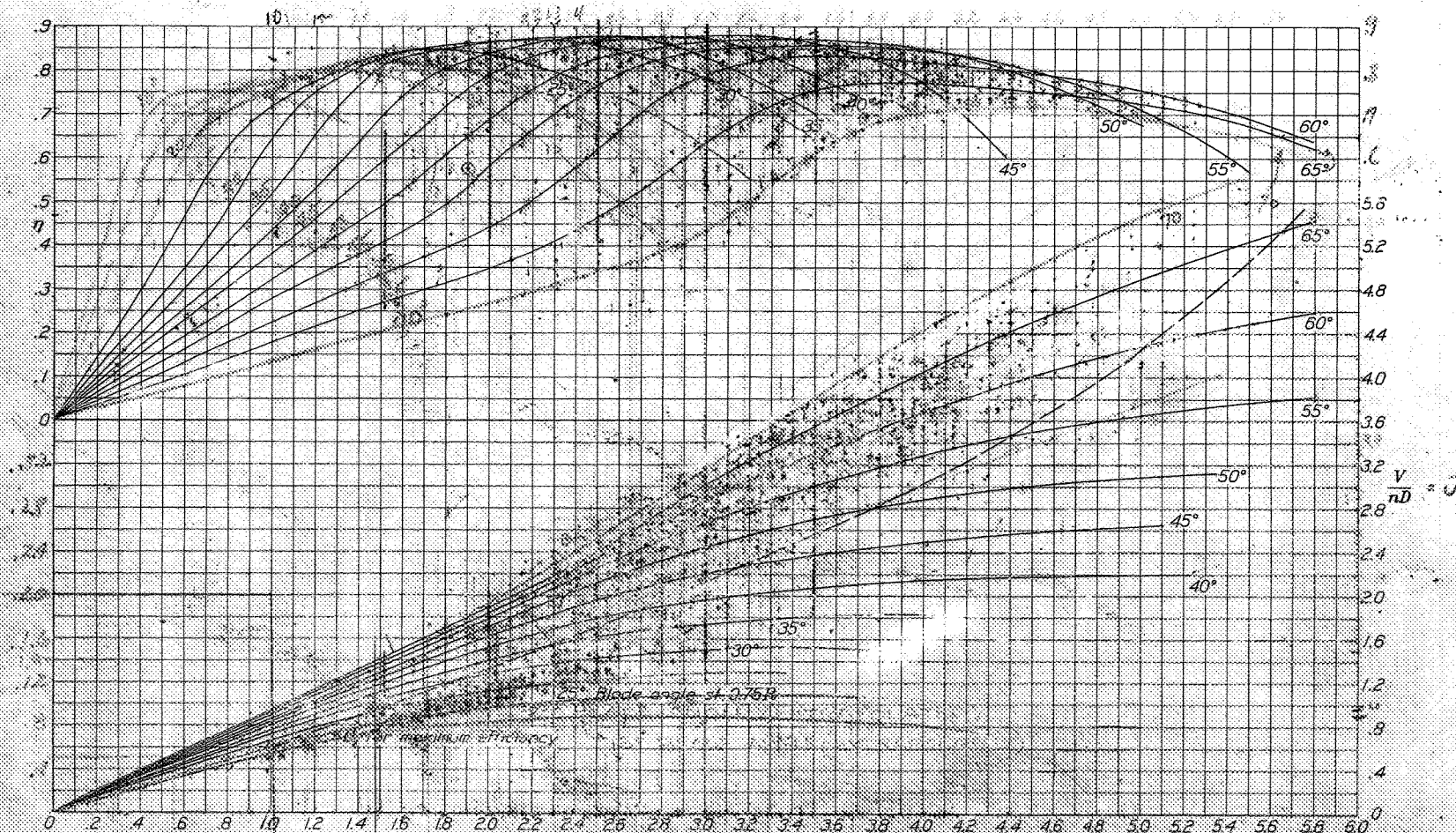


FIGURE 16.- DESIGN CHART FOR THREE-BLADE PROPELLER 3165-6 WITH CURVE.

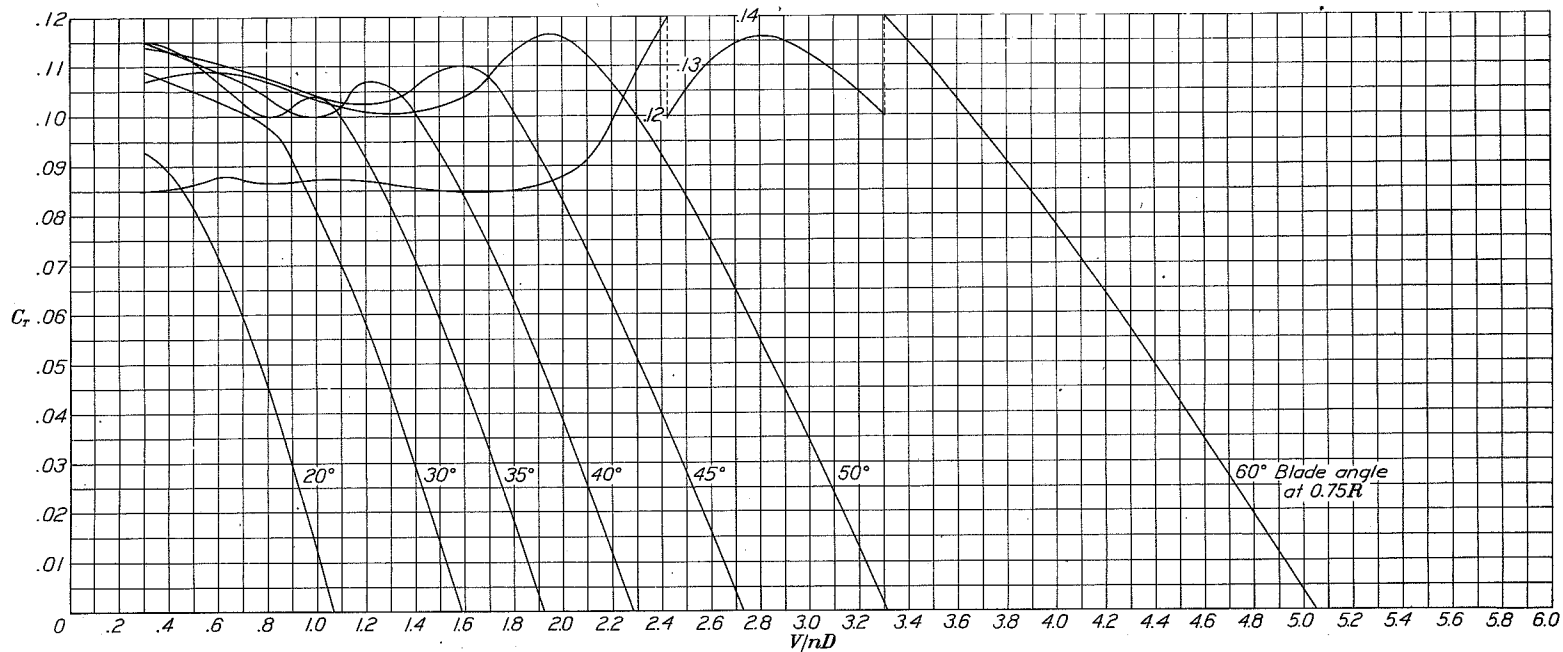


FIGURE 17.- THRUST-COEFFICIENT CURVES FOR TWO-BLADE PROPELLER 1555-2.

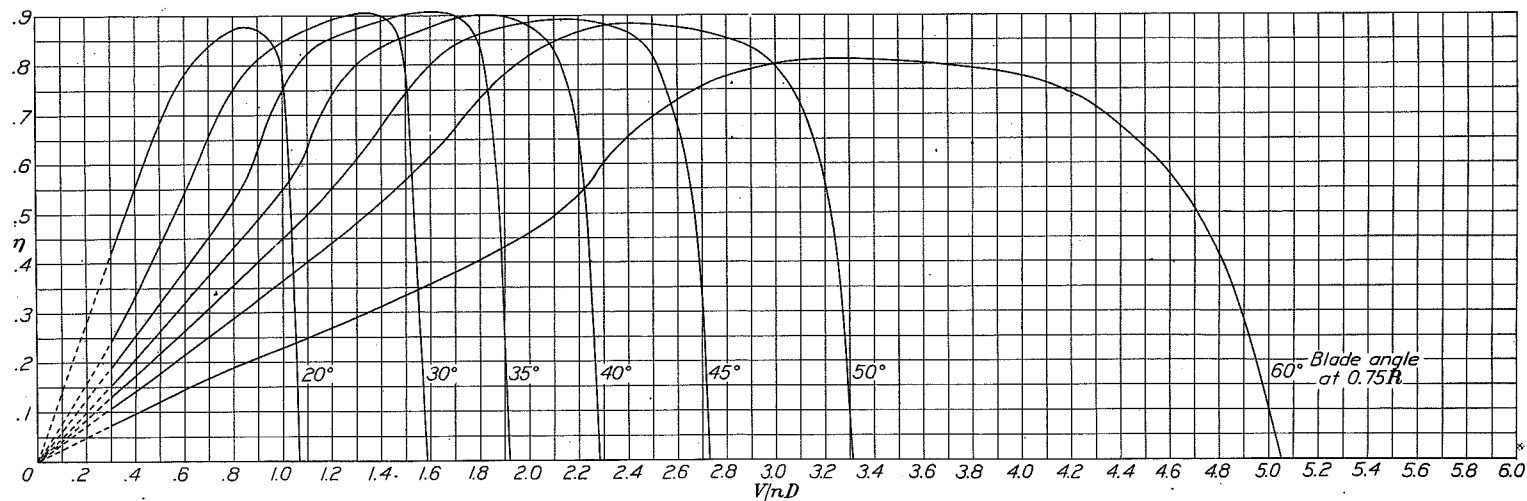


FIGURE 19.- EFFICIENCY-CURVES FOR TWO-BLADE PROPELLER 1555-2.



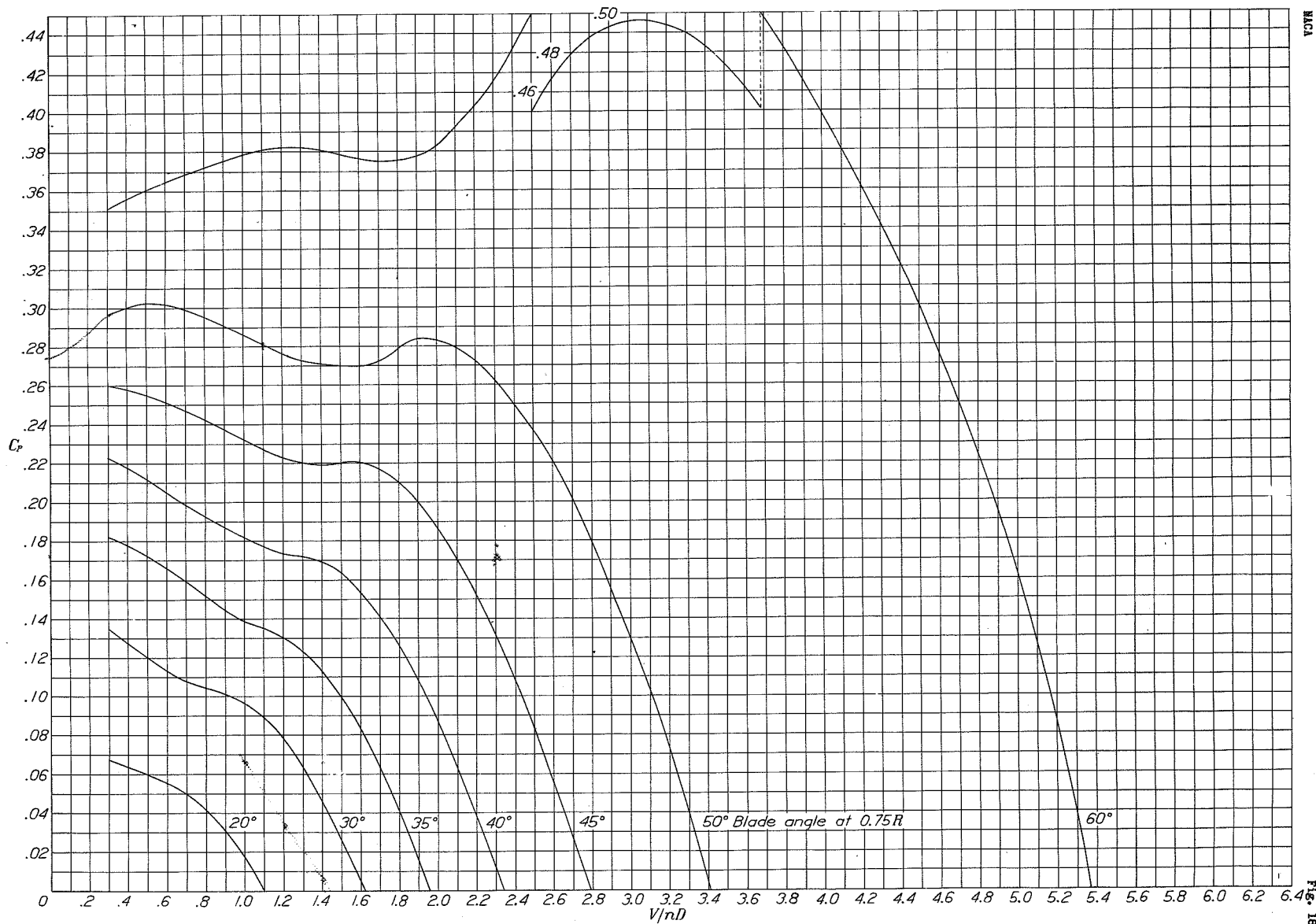


FIGURE 18.- POWER-COEFFICIENT CURVES FOR TWO-BLADE PROPELLER 1555-2.

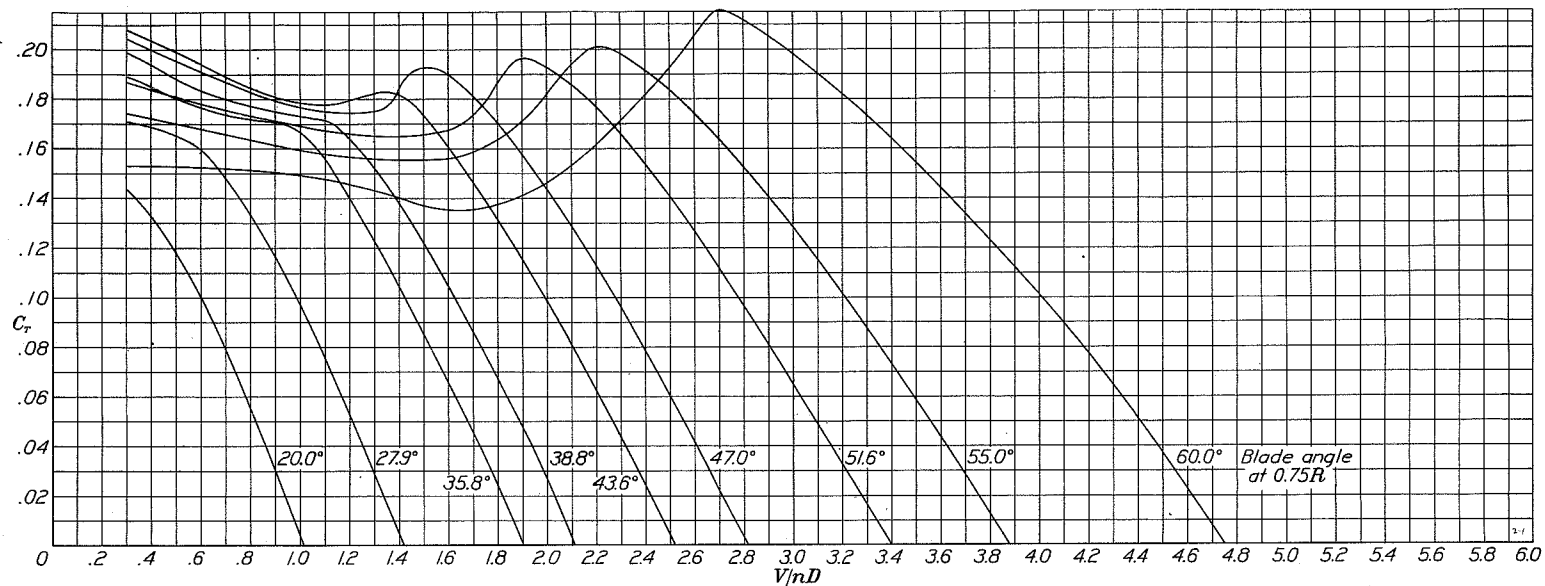


FIGURE 21.- THRUST-COEFFICIENT CURVES FOR THREE-BLADE PROPELLER 6193A-3.

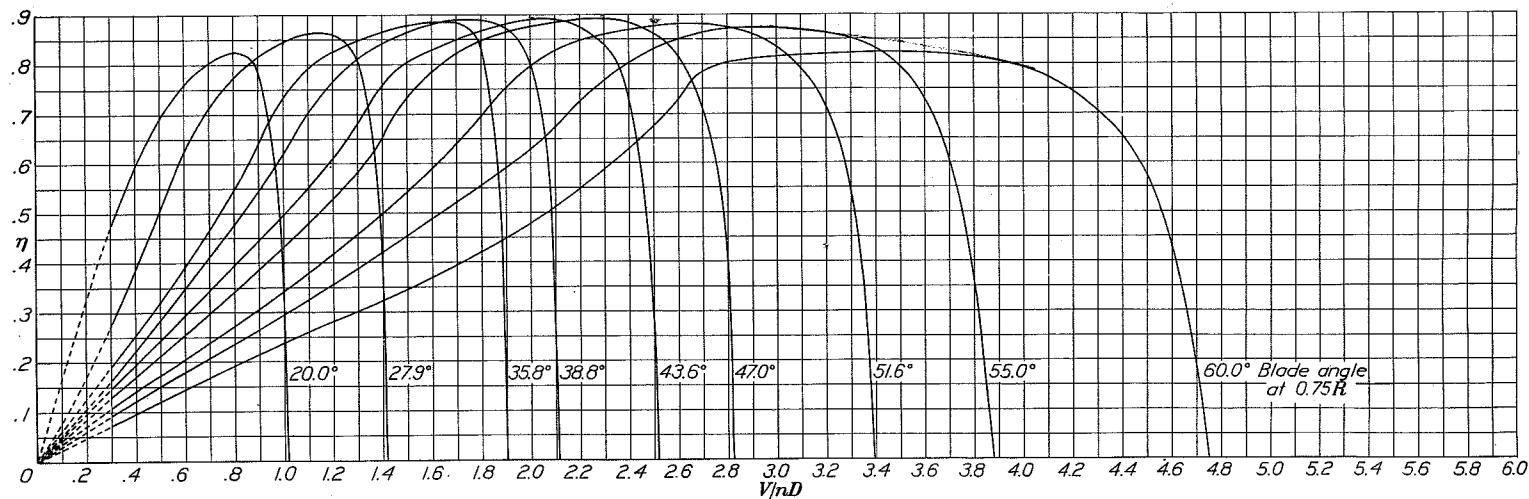


FIGURE 23.- EFFICIENCY-CURVES FOR THREE-BLADE PROPELLER 6193A-3.

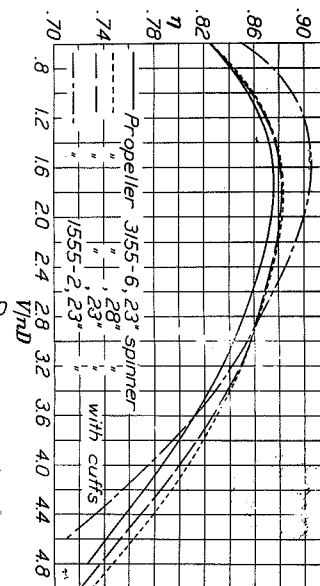


FIGURE 20.- ENVELOPE COMPARISONS OF SEVERAL PROPELLER-SPINNER-CUFF COMBINATIONS.

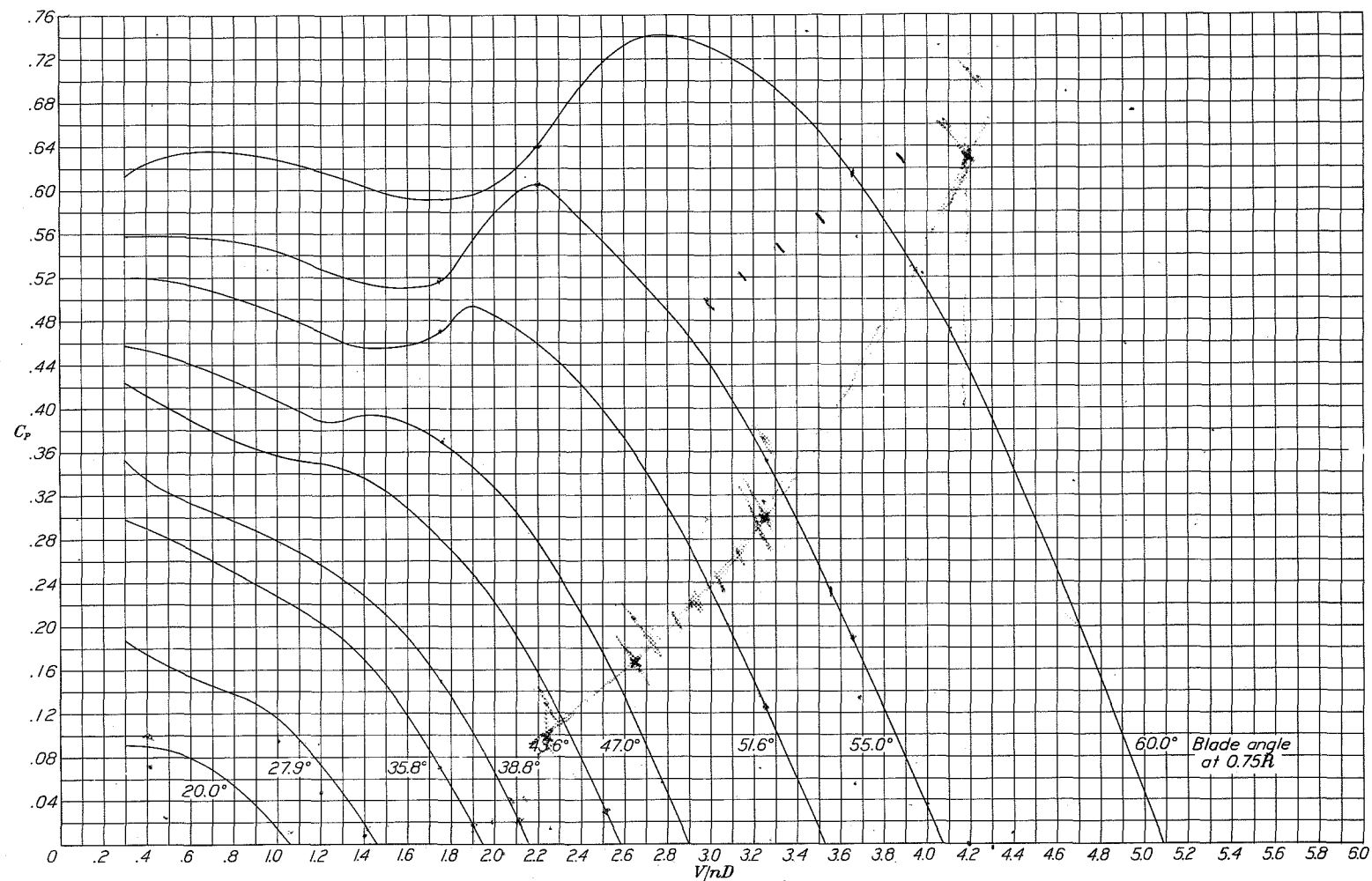


FIGURE 22.- POWER-COEFFICIENT CURVES FOR THREE-BLADE PROPELLER 6193A-3.

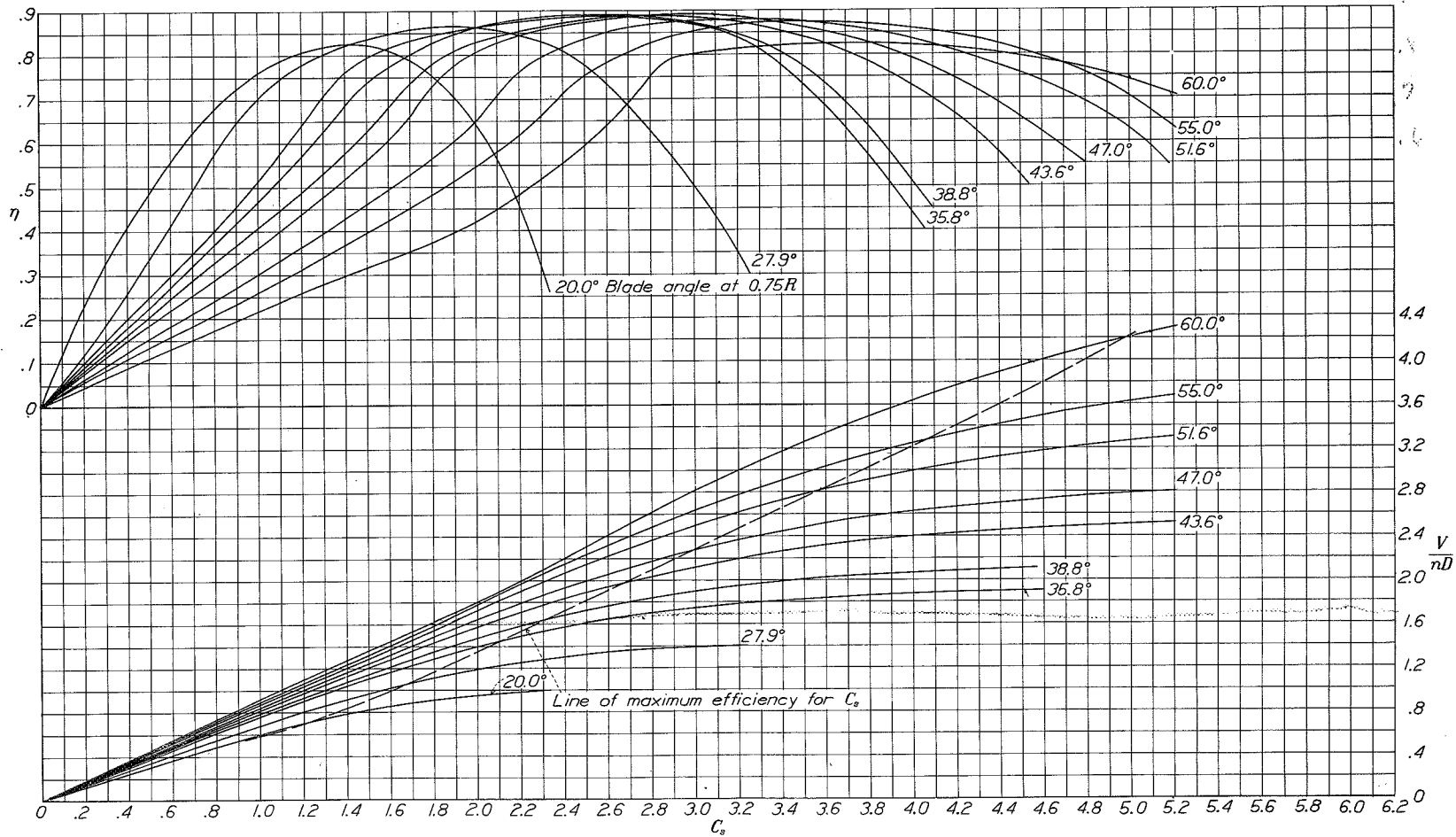


FIGURE 24.- DESIGN CHART FOR THREE-BLADE PROPELLER 6193 A-3.